Algorithm Theoretical Basis Document (ATBD) for the Conical-Scanning Microwave Imager/Sounder (CMIS) Environmental Data Records (EDRs)

Volume 10: Snow Cover/Depth EDR

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REVISION HISTORY

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RELATED CMIS DOCUMENTATION

Government Documents

Title	Version	Authorship	Date
CMIS SRD for NPOESS Spacecraft and Sensors	3.0	Associate Directorate for Acquisition NPOESS IPO	2 March 2001

Boeing Satellite Systems Documents

Title		Covering
ATBD for the CMIS TDR/SDR Algorithms		
ATBD for the CMIS EDRs	Volume 1: Overview	Part 1: Integration
		Part 2: Spatial Data Processing • Footprint Matching and Interpolation • Gridding • Imagery EDR
	Volume 2: Core Physical Inversion Module	
	Volume 3: Water Vapor EDRs	Atmospheric Vertical Moisture Profile EDR Precipitable Water EDR
	Volume 4: Atmospheric Vertical Temperature Profile EDR	
	Volume 5: Precipitation Type and Rate EDR	
	Volume 6: Pressure Profile EDR	
	Volume 7: Cloud EDRs	Part 1: Cloud Ice Water Path EDR
		Part 2: Cloud Liquid Water EDR
		Part 3: Cloud Base Height EDR
	Volume 8: Total Water Content EDR	
	Volume 9: Soil Moisture EDR	
	Volume 10: Snow Cover/Depth EDR	
	Volume 11: Vegetation/Surface Type EDR	
	Volume 12: Ice EDRs	Sea Ice Age and Sea Ice Edge Motion EDR Fresh Water Ice EDR
	Volume 13: Surface Temperature EDRs	Land Surface Temperature EDR Ice Surface Temperature EDR

Title		**Covering**
	Volume 14: Ocean EDR Algorithm Suite	Sea Surface Temperature EDR Sea Surface Wind Speed/Direction EDR Surface Wind Stress EDR
	Volume 15: Test and Validation	All EDRs

Bold = this document

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1. Abstract

The CMIS Snow Cover/Depth EDR will be retrieved by a robust algorithm based on local spectral sensitivity to snow cover amount. Beginning with 20 km scale data, the algorithm detects dry-snow cover using a globally-tuned spectral decision tree similar to heritage algorithms. Spatial analysis of the detection imagery provides bare and snow-covered cells which are then used as local calibration points relating a spectral gradient ratio to snow cover amount. The algorithm derives snow cover amount for all cells using the localized relationship to spectral gradient. The algorithm also includes a wet snow assessment module and its products include the snow cover EDR, a dry-snow detection flag, and quality control factors. In nominal algorithm operations, the primary inputs are atmospheric Core Module-retrieved emissivities (18-89 GHz) and surface temperature. Emissivity inputs provide data that are sensitive to surface composition and corrected for interfering temperature and atmospheric effects using the full complement of CMIS channels. A separate algorithm module provides the dry-snow detection flag to the Core Module using direct top-of-atmosphere brightness temperature inputs. In this ATBD we describe the algorithm's physical basis and mathematical and logical structure, inputs, implementation and data flow including integration within overall CMIS processing, and expected retrieval performance based on SSM/I data tests. Performance is expected to meet or exceed all EDR requirements except for cell size (requirement is 12.5 km). Algorithm calibration procedures, testing, and operational considerations are also discussed.

2. Introduction

2.1. Purpose

The purpose of this document is to provided all the information necessary to understand, operate, further develop, and use the products from the CMIS snow cover retrieval algorithm. The CMIS SRD (NPOESS IPO, 2000) specifies the EDRs' required (threshold level) operational and performance characteristics including definitions, spatial resolution, and measurement range and uncertainty. The integrated snow algorithm (Core Module plus snow algorithm) its nominal performance specifications by deriving its products solely from CMIS brightness temperature observations. Furthermore, the algorithm reports additional products that extend the retrieval capabilities and aid quality control.

Section 3 summarizes the EDR requirements either specified in the SRD or derived from it. It contains a historical background and physical basis for the proposed algorithm, and it describes the instrument characteristics and data from all sources necessary to meet NPOESS requirements.

Section 4 describes the physical parameterizations relevant to the snow retrieval algorithm. We also provide algorithm processing flow diagrams including dependencies within the overall processing flow and list input and output fields and ancillary databases.

Section 5 real-data test results and provides measurement uncertainty and other performance estimates based on the tests. These tests are used to demonstrate that the algorithm products will meet its nominal predicted performance specifications. We describe the environmental conditions under which we expect the retrievals to meet requirements, not to meet requirements, or to degrade substantially. We also summarize special constraints, limitations, or assumptions made in algorithm parameterization or testing that may limit the algorithm's applicable domain or necessitate post-launch adjustments based on specific systematic contributions in order to meet performance estimates.

Section 6 discusses algorithm calibration points and outlines the steps necessary to transition algorithm operation from heritage-data to CMIS-data inputs. We outline considerations for pre- and post-launch calibration and validation efforts, including needed measurement capabilities and hardware, field measurements, and existing sources of truth data.

Section 7 describes practical considerations including numerical computation considerations, algorithm quality control and diagnostics, exception and error handling, and archival requirements.

2.2. Document Scope

The *ATBD for the CMIS Snow Cover/Depth EDR* covers algorithm operations beginning with the ingestion of earth-gridded Core Module products (surface effective broad-band atmospheric window-channel emissivities and effective emitting temperature) and concluding with the reporting of snow cover amount, a dry-snow detection flag, and other related algorithm products on the same earth-grid. Preceding sensor data processing steps are covered in the *ATBD for SDR Processing* and *ATBD for the Core Physical Inversion Module* (AER, 2000). The ATBD also describes brightness temperature module operations beginning with top-of-atmosphere brightness temperatures and concluding with the reporting of a snow flag. This ATBD provides outlines for continued algorithm development and advancement and for pre- and post-launch calibration/validation efforts. These outlines are intended to be reviewed and revised prior to launch as new data sources and research become available.

3. Overview and Background Information

3.1. Objectives of the snow EDR retrieval

The snow cover EDR is a specific measurement that CMIS must perform to complete the mission objectives stated in the SRD: "The mission of CMIS is to provide an enduring capability for providing measurements on a global basis of various atmospheric, land, and sea parameters of the Earth using microwave remote sensing techniques. The CMIS instrument will collect relevant information from a spaceborne platform, and utilize scientific algorithms to process that information on the ground into designated [EDRs]." (SRD, section 3.1.7)

The SRD requires that the CMIS snow algorithm retrieve snow cover over global land areas. Snow cover is the percentage of a retrieval cell covered by snow. The CMIS snow algorithm will provide instantaneous estimates for 20 km square cells of total snow cover in clear and cloudy (non-precipitating) conditions; it will also provide a 20 km dry-snow detection flag. The algorithm will assess the possibility that a cell contains wet snow by comparing instantaneous spectral measurements to measurements within the past 24 hours. Where wet snow is indicated, the algorithm uses the corresponding prior snow cover as the current estimate. An additional algorithm module will provide a dry-snow detection flag based on brightness temperature inputs consistent with heritage approaches (for example, Ferraro et al., 1996). In addition to continuity with heritage retrievals, the snow detection products will be valuable for monitoring regional climate factors and real-time local conditions whether clear, cloudy, day, or night. The data may be input to regional hydrological and meteorological models as well as longer-term climate models. Snow cover will also be useful for water storage assessment and runoff prediction.

To provide the dry-snow detection product to other algorithms (namely, the Core Module), the brightness temperature module will be executed early in the processing flow. The snow cover algorithm—which uses emissivity and temperature inputs from the Core Module—also provides snow cover for the vegetation/surface type retrieval and will therefore be executed first. The algorithm will also provide quality control products.

CMIS snow cover will complement a similar snow cover EDR required for VIIRS. Whereas CMIS can make instantaneous measurements for dry-snow in non-precipitating conditions, the higher-resolution VIIRS retrieval will require clear skies and may have reduced skill with low solar zenith angle or nighttime conditions. Where VIIRS measurements are possible they may be better able to map snow cover where wet or thin snow are present.

3.2. Summary of EDR requirements

3.2.1. SRD Requirements

The text and tables below are the portions of CMIS SRD section 3.2.1.1.1.1 that apply directly to the snow algorithm. Shading indicates attributes not addressed at all in this document.

Snow Cover/Depth **TRD App D Section 40.6.3**
Horizontal and vertical extent of snow cover. As a threshold, only the fraction of snow cover in the specified horizontal cell is required, regardless of depth. As an objective, fraction of snow cover for snow having a specified minimum depth is required in the specified horizontal cell for a set of specified minimum depths.

Table 3-1: SRD Requirements for the Snow Cover/Depth EDR

Para. No.		Thresholds	Objectives
C40.6.3-1	a. Horizontal Cell Size	12.5 km	1 km
C40.6.3-2	Deleted		
C40.6.3-3	b. Horizontal Reporting Interval	12.5 km	1 km
C40.6.3-4	c. Snow Depth Ranges	> 0 cm (Any Snow Thickness)	> 8 cm, > 15 cm, > 30 cm, >51 cm, >76 cm
C40.6.3-5	d. Horizontal Coverage	Land	Land & Ice
C40.6.3-6	e. Vertical Coverage	> 0 cm	0 - 1 m
C40.6.3-7	f. Measurement Range	0 – 100%	0 - 1 per snow depth category
C40.6.3-8	g. Measurement Uncertainty	20 % (snow/no snow)	10 % for snow depth
C40.6.3-9	Deleted		
C40.6.3-10	h. Mapping Uncertainty	3 km	1 km
C40.6.3-11	Deleted		
C40.6.3-12	k. Swath Width	1700 km (TBR)	3000 km (TBR)

In addition to these requirements, the SRD specifies:

1. "Science algorithms shall process CMIS data, and other data as required, to provide the [EDRs] assigned to CMIS." (SRD, paragraph SRDC3.1.4.2-1)
2. "Specified EDR performance shall be obtained for any of the orbits described in paragraph 3.1.6.3 …" (SRDC3.1.6.3-2)
3. "As a minimum, the EDR requirements shall be satisfied at the threshold level." (SRDC3.2.1.1.1-3)
4. "… the contractor shall identify the requirements which are not fully satisfied, and specify the conditions when they will not be satisfied." (SRCD3.2.1.1.1-4)
5. "… CMIS shall satisfy the EDR Thresholds associated with cloudy conditions under all measurement conditions …" (SRD SRDC3.2.1.1.1.1-1)

Also note that the CMIS system consists "of all ground and spaceborne hardware and software necessary to perform calibrated, microwave radiometric measurements from space and the software and science algorithms necessary to process … these measurement into a format consistent with the requirements of the assigned [EDRs]." (SRD, section 3.1.1)

3.2.2. Requirements interpretations

We infer the following statements as either direct consequences or clarifications of the SRD requirements stated above and take them as requirements to be satisfied by the snow algorithm or to be addressed through algorithm performance evaluation:

1. The threshold measurement uncertainty is in absolute units of percent snow cover; it is not relative to the true snow cover percentage, in which case, for example, the measurement uncertainty at10% snow cover would be 1% snow cover.

3.2.3. Derived requirements on the snow algorithm

Other algorithms have imposed additional requirements on the snow algorithm for pre-classification of the surface based on top-of-atmosphere brightness temperatures.

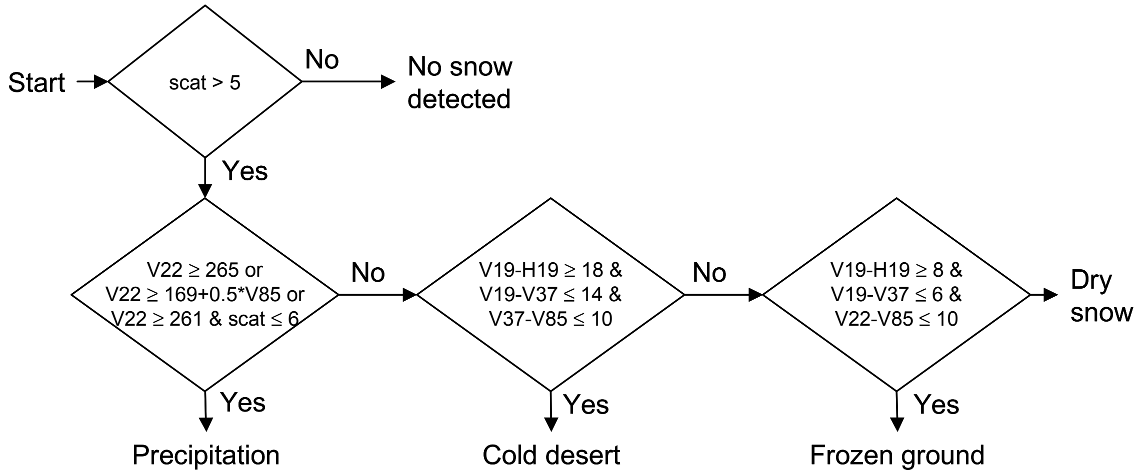
- The Core Module requires a binary snow-or-bare flag retrieved from brightness temperatures on composite footprint retrieval cells. At least TBD% of cells with 50% or more snow must be flagged. Percentage of bare cells (0% snow) incorrectly flagged as snow may be as high as TBD%. Detection of snow on ice is not required.
- The Vegetation/Surface Type algorithm requires a binary snow-or-bare flag with 20 km HCS. At least 70% of cells with 50% or more snow must be flagged and the percentage of bare cells (<50% snow) incorrectly flagged as snow must be low enough to allow 70% correct typing for each of the other required types. Detection of snow on ice is not required.

3.3. Historical and background perspective of proposed algorithm

Snow detection and depth algorithms have been applied to CMIS-heritage instruments (e.g., SMMR and SMM/I) dating back to at least 1978 (e.g., Ferraro et al., 1996). There is no operational history of snow cover percentage measurement. Heritage retrievals were nominally limited to the horizontal spatial resolutions (HSR) of the 19 GHz channels—55 km for SMMR and 69 km for SSM/I—although they may have resolved finer features at the 37 GHz resolutions, 27 and 37 km. Algorithms for the soon-to-be-launch AMSR-E (EOS Aqua platform) will generate snow storage index data (Chang and Rango, 1999). The AMSR 19 and 37 GHz HSR are 28 and 14 km, respectively.

Versions of the dry (scattering) snow detection decision tree algorithm develop by Grody (1991) and Grody and Basist (1996) for SSM/I measurements have been successfully tested globally. Figure 3-1 gives the brightness temperature version of the algorithm from Ferraro et al. (1996). Grody and Basist (1996) compared 1988-1992 monthly Northern Hemisphere snow covered area derived from the decision tree to the area calculated from the operational product derived from subjective analysis of imagery. The difference between the two areas never exceed +/-3% which is at least partially attributable to undetected wet and thin snow and synchonization between the two products.

Figure 3-1: SSM/I brightness temperature snow detection algorithm (Ferraro et al., 1996)



The CMIS EDR requirements above build on the heritage products by imposing a set of additional attributes and performance criteria. First is the 12.5 km horizontal cell size requirement which represents a significant improvement upon the current (SSM/I) and past (SMMR) operational products. Second is that snow cover fraction is required whereas heritage algorithms provide snow detection or depth. The following items summarize some of the defining attributes of the CMIS system, requirements, and retrieval approach:

1. The CMIS system will perform atmosphere temperature and water vapor sounding using channels that are either completely or partially insensitive to the surface conditions. To produce the snow EDR, the snow algorithm will ingest surface emissivities and effective temperature retrieved by the Core Module atmospheric algorithm (see *ATBD for the Core Physical Inversion Module*, AER 2000). The Core Module can retrieve emissivity accurately over a wide range of surface and atmospheric conditions and functions as a "weather filter" for snow EDR retrievals.
2. The SRD-required threshold product is snow cover percentage. The SRD does not require a snow detection product for the Snow Cover/Depth EDR and places no requirements on snow detection correct typing performance at 12.5 km HCS. The Vegetation/Surface Type algorithm requires snow detection (predominant or >50% snow cover) at 20 km HCS with 70% probability of correct typing over all types. This requirement will be met by the snow algorithm.

3.4. Physics of Problem

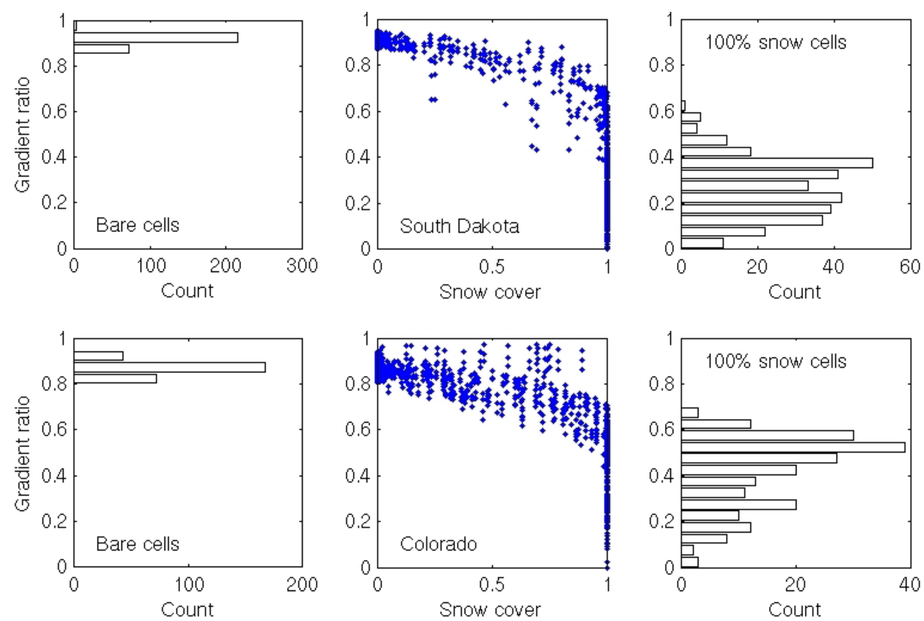
Passive microwave retrievals of snow parameters rely on snow's distinctive spectral signatures. Dry snow (snow at temperatures less than 273 K) has low microwave absorption characteristics commensurate with the low loss factor of ice (~0.001-0.1) and its high fraction of air spaces (up to 85%). Low absorption allows for scattering in the snowpack that effectively attenuates radiation emitted below and low in the snowpack while scattering back to the sensor cold down-welling atmospheric radiation. The effect is most often manifested as brightness temperatures (or emissivities) that are successively lower from 19 to 85 GHz.. In contrast, melting snow (T = 273 K) is very lossy due to the high loss factor of water (~7-40) while lacking sufficient volume to produce a reflecting surface with a strong dielectric boundary. The emissivity of wet snow may approach 1 at all microwave frequencies.

As discussed above, the presence of dry snow may be readily detected using a series of spectral tests that distinguish scattering from non-scattering targets and discriminate between snow and other scattering from some deserts, precipitation, and frozen ground. For successful retrieval of snow cover or snow depth there must be a continuous spectral response to either parameter that exceeds the spectral variability of snow (and bare ground) due to other factors—temperature gradients, snow grain size distribution, snow stratigraphy, soil substrate temperature and water content, vegetation cover, etc. Figure 3-2 illustrates how the spectral signature of snow varies as a function of snow cover amount (from visible imagery) and the distribution within bare and 100% snow covered cells. The plots show the scaled gradient ratio from SSM/I data where gradient ratio is defined as:

$$g = \frac{\mathrm{TB19V} - \mathrm{TB85V}}{\mathrm{TB19V} + \mathrm{TB85V}}\,. \qquad (1)$$

As described in section 5.5.1, up to four SSM/I passes were matched to each truth scene—here centered on South Dakota and Colorado. In order to minimized differences from region to region, the gradient ratios from each region are scaled to the 0-1 range based on the minimum and maximum g in the region. The center plots show scaled g vs. snow cover and the left and right plots show the distribution of g among bare and 100% snow covered cells, respectively.

Figure 3-2: SSM/I scaled gradient ratio variation with true snow cover for two regions



The spectral gradient variability within the snowpack is much higher than in the bare cells. This is also reflected in the dependence of g on snow cover, especially in the Colorado scene. To accurately retrieve snow cover from the gradient, an estimate of the spectral characteristics of snow within the mixed cells must be made. The high variability within the snowpack rules out the straight forward use of 100% snow cells—if they could be distinguished—as a calibration source for mixed-cell snow spectrum. Less variability in the South Dakota scene suggests that the spectral signature of snow within the mixed cells is more uniform and that the geographical scale of variation may be longer than in the Colorado scene. If snow's spectral variation is mostly a geographical feature, then variability may be reduce by further localization of the data. The challenge for the snow cover algorithm is to determine how to best estimate snow's spectral signature using cells where the snow cover can be accurately assessed and the cell's snow signature is most likely to be similar to that in the mixed cells.

3.5. Instrument characteristics and derived requirements

CMIS is a conically-scanning microwave radiometer with window channels—frequencies chosen to avoid atmospheric absorption lines—around 6, 10, 19, 37, and 88 GHz and atmospheric sounding channel families around 23, 50-60, 60, 166, and 183 GHz. The instrument rotates continuously at 31.6 rpm on an axis perpendicular to the ground taking observations along nearly semi-circular arcs centered on the satellite ground track. Successive arcs scanned by a single sensor channel are separated by about 12.5 km along-track (depending on satellite altitude.) Calibration data is collected from a source (hot) and deep-space reflector (cold) viewed during the non-earth-viewing portion of the rotation cycle. Each observation (or sample) requires a finite sensor integration time which also transforms the sensor instantaneous field of view (IFOV)—the projection, or footprint, of the antenna gain pattern on the earth—into an observation effective field of view (EFOV). The start of each sample is separated by the sample time which is slightly longer than the integration time. The sample time is t_s = 1.2659 ms for all channels with the exception of 10 GHz (exactly $2t_s$) and 6.8 GHz ($4t_s$). All samples fall on one of three main-reflector scan-arcs or a single secondary-reflector scan arc (166 and 183 GHz channels only).

Sensor sample processing (described in the *ATBD for Common EDR Processing Task*, AER, 2000) creates composite measurements which are the spatial weighted superposition of a contiguous group of sensor samples. Although not exact, the process is designed to match observations from different channels to a single reference footprint: The composite fields-of-view (CFOVs) from different channels are more closely matched and collocated than the corresponding EFOVs. In addition, because sensor noise (as measured in NEDT) is both random and independent between samples, the effective NEDT of composite footprints may be reduced (amplified) if the square-root of the sum of squared sample weights is less than (greater than) one. The snow algorithm uses data processed to match 20x20 km reference footprints.

Table 3-2 lists specific characteristics relevant to the snow EDR for each sensor channel. (Sounding channel families around 50-60 and 183 GHz are listed as groups. Other channels that are neither H or V pol. are not listed.) Channels that are applied to snow EDR retrieval are marked either as required to meet or approach threshold requirements (X) or used to meet or approach objectives (O). Additional channels above 18 GHz can enhance performance of the Core Module's emissivity retrieval product.

Table 3-2: Instrument Characteristics and Snow EDR Channel Applications

	SELECTED SENSOR CHANNEL SPECIFICATIONS														
Channel prefix	6		10		18		23		36		60VL	89		166	183V
Channel suffix(es)	V	H	V	H	V	H	V	H	V	H	A,…	V	H	V	A,B,C
Frequency range [GHz]	6.45-6.8		10.6-10.7		18.6-18.8		23.6-24.0		36.0-37.0		50-60	87.0-91.0		164.5-167.5	173.4-193.3
Snow EDR channel applications[1]					X	X	X	O	X	X	O	X	X	O	O
Single-sample NEDT [K]	0.47		1.2		1.3		1.1		0.66		2.8[2]	0.57		2.7	2.7[2]
20 km composite max/min NRF	--		--		0.39/		0.44/		0.48/		0.41/	0.39/		0.44/	0.40/
Earth incidence angle	55.9		58.3		53.8		53.8		55.9		55.9	55.9		55.7	55.7
Cross-scan EFOV [km]	66.5		46.8		23.1		21.3		16.9		15.0	14.9		17.4	15.5
Along-scan EFOV [km]	40.1		24.9		14.2		13.3		10.8		8.2	8.3		9.6	9.6
Integration time [ms]	5		2.5		1.2		1.2		1.2		1.2	1.2		1.2	1.2
No. EFOV per scan															
Swath width [km]															

[1] X = channel required to meet or approach threshold; O = channel used to meet or approach objectives.
[2] Figures are for lowest frequency in set. For illustrative purposes only.

3.6. Requirements for cross sensor data (NPOESS or other sensors)

The present design of the snow algorithm does not require any data from sensors other than CMIS.

3.7. Required, alternate, and enhancing algorithm inputs

3.7.1. CMIS data and product requirements

Table 3-3: Inputs from other CMIS algorithms

CMIS Products	Usage
Spectral Emissivity from Core Module Algorithm	-Primary snow EDR retrieval input -Required at 18V, 18H, 36V, 36H, 89V, and 89H at 20 km HCS -Required at current time
Surface temperature from Core Module Algorithm	-Primary snow EDR retrieval input -Required at 20 km HCS -Required at current time
Precipitation Flag from Core Module Algorithm	-Quality control input -Required at current time, 20 km HCS

3.7.2. Other NPOESS Sensor Data and Product Inputs

No sensor data or products are required from other NPOESS instruments.

3.7.3. External Data Requirements

Table 3-4: External data requirements

External Data	Usage
Surface Database	-Provides static surface data indicating if land is present in cell

3.7.4. Alternate and Enhancing Data Sources

Table 3-5: Alternate and enhancing data sources

Data Source	Usage
CMIS: 18V, 18H, 23V, 36V, 36H, 89V, and 89H TBs	-Alternatives to spectral emissivity and surface temperature inputs
Prior spectral gradient database from snow algorithm	-Snow cover EDR retrieval input for wet snow detection -Required at least twice within 24 hours prior to current time and at same times as prior snow cover retrieval database
Prior snow cover database from snow algorithm	-Snow cover EDR retrieval input for wet snow detection -Required at least twice within 24 hours prior to current time and at same times as prior spectral gradient database

4. Algorithm description

4.1. Theoretical description of algorithm

The snow detection and snow cover algorithms are based on experimental observations of snow cover effects on sensor-measured brightness temperatures. As discussed in section 3.4, these effects are similarly manifested in surface emissivities. The snow cover module is expressed in terms of emissivity and surface temperature inputs (but may be easily converted to brightness temperature inputs by changing parameters); snow detection modules are provided for either emissivity and temperature inputs or brightness temperature inputs. All of the algorithm modules are empirically-based and require the specification of tunable parameters such as thresholds, snow cover amounts, and coefficients. The algorithm currently operates with working values for these parameters. The snow cover EDR algorithm first assesses the presence of snow using a series of emissivity and temperature comparisons. The algorithm then estimates snow cover based on a cell's 18-89 GHz spectral gradient and the gradients of cells in the region assessed to be bare and mostly snow-covered. An additional step detects and adjusts for wet snow using prior gradient and snow cover observations at the same location within a 24 hour window.

The baseline algorithm retrieves snow cover from emissivities retrieved by the CMIS Core Physical Inversion Module. The *ATBD for the Core Physical Inversion Module* (AER, 2000) describes this process in more detail. The Core Module removes atmospheric effects and retrieves surface effective emitting temperature T_{eff} and spectral emissivity e from top-of-atmosphere brightness temperature measurements. The Core Module uses a plane parallel model of the atmosphere whose lower boundary condition is parameterized by T_{eff} and e, where $e \equiv 1 - r$ and r is the surface specular reflectivity. The brightness temperature-based snow detection algorithm provides a spectral pre-classification for the Core Module. Since the Core Module requires detection of the spectral signature of snow, there is no additional adjustment for wet snow which is spectrally dissimilar to dry snow. The Core Module flags precipitation and passes atmospheric retrieval quality control values that are used by the snow cover EDR algorithm

Table 4-1 summarizes algorithm design trades leading to the baseline snow algorithm design. The following sections give detailed descriptions of the mathematics of adopted trades and their role in the algorithm processing flow.

Table 4-1: Algorithm design trades

Trade Study	Baseline Decision	Basis/Benefit
Spectral gradient	Base snow cover on 19-89 GHz spectral gradient	SSM/I brightness temperature retrieval test performance is best with 22-89 or 19-89 GHz
Spatial analysis	Do not use spatial analysis to retrieval snow cover	Spatial analysis does not meet threshold requirements even in simulated tests with noise-free retrievals
Emissivity-based retrieval	Support both emissivity and brightness temperature algorithm inputs. Emissivity is baseline for EDRs.	Core Module provides accurate emissivities (weather effects filtering). TB support required for Core Module preprocessing.
Gridding	Grid emissivity inputs and retrieve products on grid(s)	Gridded retrievals improve access to prior data for wet snow detection and interaction with surface type algorithm

4.2. Mathematical Description of Algorithm

Table 4-2 defines snow algorithm inputs and other variables used in this section. The following processing steps occur prior to snow algorithm processing and are described in other documents: Derivation of CMIS brightness temperatures from raw data (*ATBD for SDR Processing*, AER, 2000); footprint matching and interpolation in the sensor reference frame (*ATBD for Common EDR Processing Tasks*, AER, 2000); Core Module retrievals of surface emissivities and effective emitting temperature (*ATBD for the CMIS Core Physical Inversion Module*, AER, 2000); and mapping of sensor-gridded data to an earth-grid (*ATBD for Common EDR Processing Tasks*, AER, 2000).

Table 4-2: Definitions of Algorithm Input and Internal Model Symbols

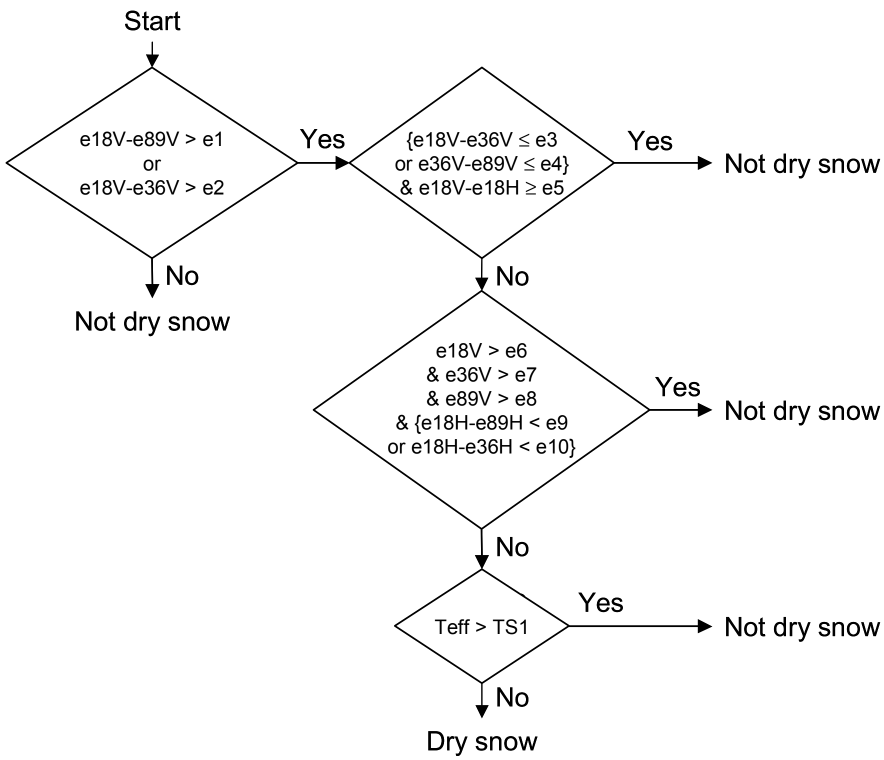
Algorithm Inputs	
*e*FP	Emissivity at frequency F and polarization P
FP	Brightness temperature at at frequency F and polarization P (used only in brightness temperature module)
T_{eff}	Surface effective emitting temperature from Core Module
Other algorithm variables	
A3	Brightness temperature-based snow detection decision tree constant
e1-e10	Snow detection decision tree emissivity constants
f_p	Snow cover constant for local algorithm calibration
g	Spectral gradient ratio
g_0, g_1	Estimated spectral gradients at 0 and 100% snow cover
g_i	Spectral gradient from i^{th} previous observation
Δg_i	Change in g since i^{th} previous observation
g_p	Spectral gradient estimate for cells with f_p snow cover
s	Retrieved snow cover amount
T1–T11	Snow detection decision tree brightness temperature constants
TS1	Snow detection decision tree surface temperature constant

Each of the following sections provides a mathematical description of a module or component of the CMIS snow algorithm. Some trivial components (namely, programming logic) are excluded. See Figure 4-3 for a processing flow diagram. Note that all of the coefficients and constants are tunable parameters whether or not they are given an explicit value here

Dry snow detection from emissivity

The algorithm detects dry snow using gridded emissivities and surface temperature products from the Core Module. The coefficients e1-e10 and TS1 will be tuned for the CMIS channel set and comparators will be added or removed based on algorithm validation experiments.

Figure 4-1: Decision tree for dry snow detection from CMIS emissivity retrievals



Snow cover estimation

The snow detection algorithm is based on changes in the spectral gradient ratio defined as:

$$g = \frac{e18V - e89V}{e18V + e89V}. \tag{2}$$

To calibrate the snow cover-spectral gradient relationship, the algorithm selects cells from a regional scene that satisfy two sets of criteria based on dry snow detection. The first set of cells are those that fall in the center of a 3-cell x 3-cell group where no dry snow is detected. These cells are sorted by spectral gradient and the *lowest* 50% are averaged to give g_0, the spectral gradient estimate for 0 snow cover. The second set of cells are those that fall in the center of a 5x5 cell group where fraction of cells with snow detected is greater that 0.75 and less than 1. The spectral gradients of these cells are averaged to give g_p, the spectral gradient estimate for f_p snow cover. The spectral gradient estimate for 100% snow cover g_1 is given by:

$$g_1 = g_p + (1 - f_p)(g_p - g_0) / f_p. \tag{3}$$

If in a particular region there are insufficient cells that match the first or second criterion, the algorithm may use the entire set of cells detected as bare or snow, respectively. If a region has either no bare-detected cells or no snow-detected cells, then the detection product is used for snow cover—that is, bare-detected cells are set to 0 snow cover and snow-detected cells to 100% snow cover.

The algorithm computes the snow cover percent estimated for every cell in a region by interpolating in terms of the spectral gradient:

$$s = 100 * \frac{g - g_0}{g_1 - g_0}. \tag{4}$$

Additional post-processing steps limit s to the 0-100% range and set s in any cells in the center of a 5x5 cell group with no snow detected to 0.

Wet snow detection and snow cover adjustment

The algorithm detects wet snow by comparing g to previous observations no more than 24 hours old. Given N previous observations i = 1-N with spectral gradients g_i and snow cover s_i, the spectral gradient change is given by:

$$\Delta g_i = g - g_i \tag{5}$$

and the observation with the maximum spectral gradient change Δg_{max} is i_{max}. If Δg_{max} greater than Δg_w, then the current cell is assumed to be wet snow and the algorithm sets $s = s_{imax}$.

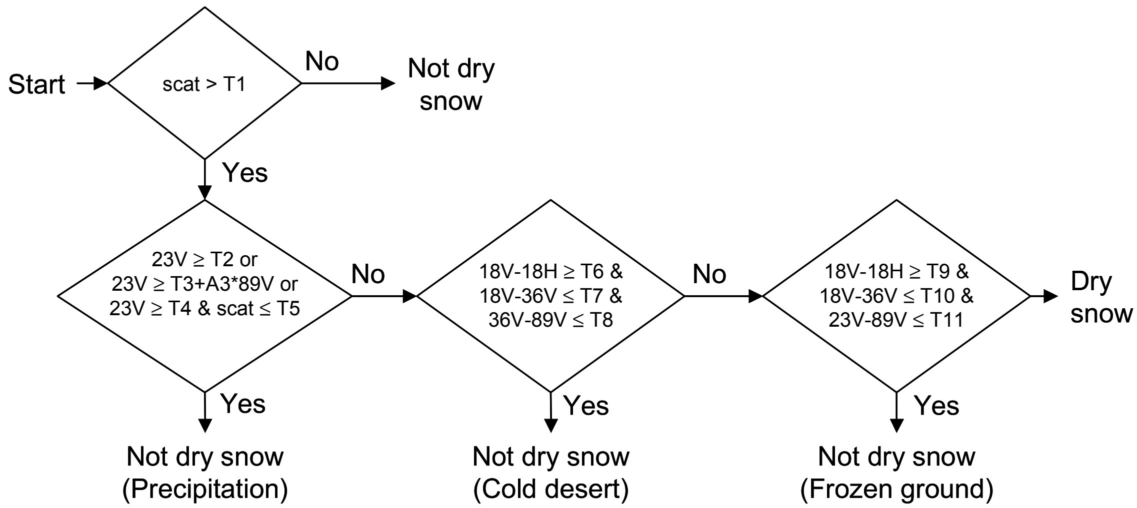
The technique is designed to consistently map snow cover even when the snow surface fluctuates diurnally between thawed and frozen. Longer periods of thaw are not detected and some false positive snow amounts lasting no more than 24 hours may occur when the cell has in fact transitioned from detectable dry snow to bare within 24 hours.

Dry snow detection from brightness temperatures

A separate module detects dry snow from brightness temperatures for use by the Core Module. The module uses the decision tree in Figure 4-2, which is based on the SSM/I decision tree in Figure 3-1 with the exception that the coefficients T1-T11 and A3 will be tuned for the CMIS channel set. Comparators may also be added or removed based on validation experiments. The symbols 18V, 18H, 23V, 36V, and 89V represent the brightness temperature at the corresponding CMIS channel. The parameter SCAT is defined as:

$$\text{SCAT} = \text{MAX}\{23V - 89V \text{ or } 18V - 36V\} \tag{6}$$

Figure 4-2: Decision tree for dry snow detection from CMIS brightness temperatures

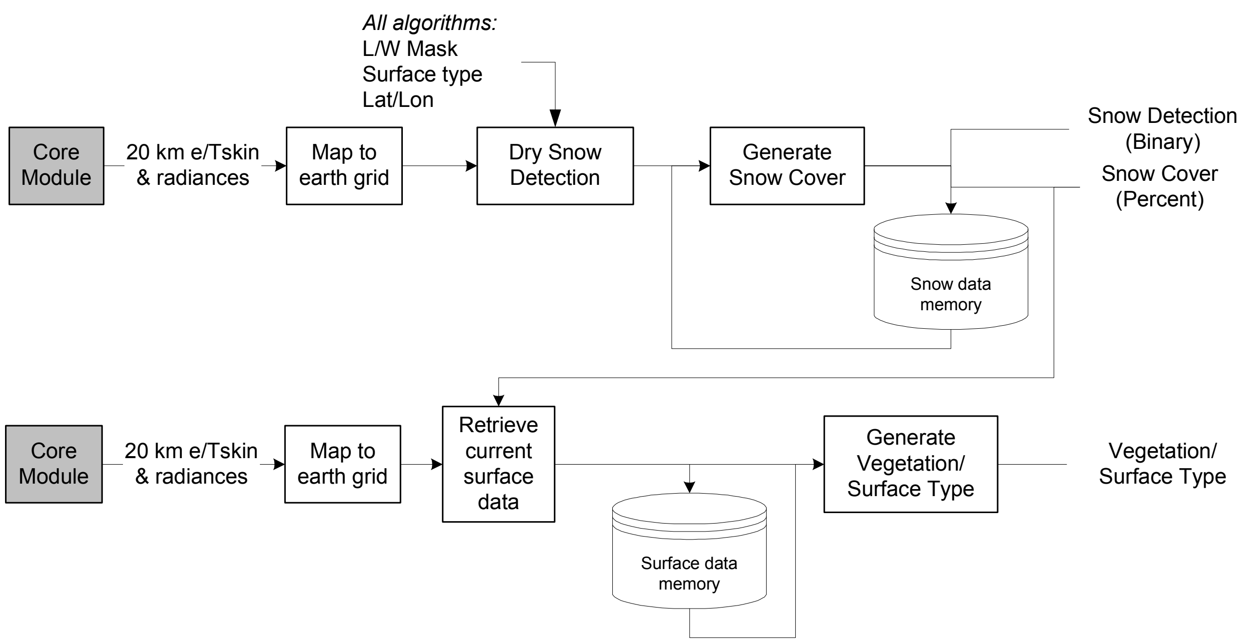


4.3. Algorithm Processing Flow

4.3.1. Processing flow for CMIS snow algorithm

Figure 4-3 shows the processing flow for the snow retrieval algorithm. Section 4.1 describes algorithm physics and section 4.2 gives the algorithm's mathematical description.

Figure 4-3: Snow algorithm processing flow diagram



4.4. Algorithm inputs

The table below summarizes the input data used by the snow algorithm. Input data requirements are described in more detail in section 3.7.

Table 4-3: Snow Cover EDR – Input Data Description

Input Data	Range
Emissivities @ 18V, 18H, 36V, 36H, 89V, 89H	0-1
Surface temperature	213-343 K
Prior spectral gradient observations	-1-1
Prior snow cover retrievals	0-1
Precipitation flag	One of {0,1}

4.5. Algorithm products

The tables below summarize the characteristics of the operational snow products.

Table 4-4: Snow Cover – Operational Product Description

Parameter	Value
Range	0-100
HCS	20 km
Units	% of cell
QC Flag	Low Quality Input Data, Missing Data

Table 4-5: Snow Flag – Operational Product Description

Parameter	Value
Range	One of {0 = bare, 1 = snow covered}
HCS	20 km
Units	binary alternatives [unitless]
QC Flag	Low Quality Input Data, Missing Data

5. Algorithm Performance

5.1. General Description of Nominal an Limited Performance Conditions

This section describes the nominal and limited performance conditions at which the threshold requirements can be achieved. Two SRD sections address special conditions. SRDC3.2.1.1.1-4: "In the event the requirements for an EDR cannot be fully satisfied, the contractor shall identify the requirements which are not fully satisfied, and specify the conditions when they will not be satisfied." SRDC3.2.1.1.1-5: "The contractor shall also specify the conditions under which it recommends delivering an EDR which is incomplete and/or of degraded quality, but which is still of potential utility to one or more users."

The following tables describe the nominal conditions under which nominal predicted performance can be achieved.

Table 5-1: Snow Cover – Nominal performance characteristics

Conditions needed to meet threshold requirements	Description	Comments/Characteristics
Atmospheric condition	• Clear or cloudy • Precipitation < 1 mm/hr	Precipitation blocks signal from surface

The following table describes the Limited Performance Characteristics under specific conditions; nominal predicted performance may not be entirely achieved under these conditions.

Table 5-2: Snow Cover – Performance under limited performance conditions

Conditions	Description	Comments/Characteristics
Precipitation	Precipitation > 1 mm/hr	No retrieval

5.2. Variance/Uncertainty Estimates

This section details snow algorithm performance estimates for each performance metric assigned to the algorithm from the following SRD attributes: *Horizontal Cell Size, Snow Depth Ranges, Vertical Coverage, Measurement Range,* and *Measurement Uncertainty*. Real-data tests with SSM/I observations (described in section 5.5) provide quantitative basis for these algorithm performance assessments.

Of the remaining attributes, *Horizontal Reporting Interval* (in addition to *Horizontal Cell Size*) is derived from the spatial properties of the sensor footprints, footprint compositing and interpolation performance, and grid definition; *Horizontal Coverage* is satisfied through the spacecraft orbit specification and algorithm definitions (that is, the snow retrieval is performed over land by definition), *Mapping Uncertainty* is satisfied by spacecraft stability and instrument pointing error requirements, and *Swath Width* is met primarily through spacecraft orbit and instrument specifications and footprint compositing and interpolation performance. For related algorithm performance assessments, see the *ATBD for Footprint Matching and Interpolation* and the *ATBD for Common EDR Processing Tasks*. Note that Horizontal Cell Size is an explicit part of the assessment of measurement uncertainty and other algorithm retrieval performance metrics. That is, quantitative performance estimates represent comparisons of retrieved products and true cell-average products.

5.2.1. Binning Categories

Variance and uncertainty estimates are stratified by reporting performance in bins. Each bin represents a range of values for a particular environmental condition. Snow cover measurement uncertainty is binned only by (true) snow cover percentage with the following ranges: 0 (exact), >0-20, 20-40, 40-60, 60-80, 80-<100, and 100% (exact). Bins with exactly 0 and 100% snow cover are considered exclusively because the vast majority of cases globally fall into these bins.

5.2.2. Horizontal Cell Size Performance

The snow cover horizontal cell size depends on snow cover spatial characteristics and the horizontal spatial resolution and sampling of the sensor. As shown in Table 3-2, channels used by the snow cover algorithm range in HSR from about 15 (89 GHz) to 23 (18 GHz) km. From tests described in section 5.5.2 we concluded that threshold measurement uncertainty requirements could not be met for cells smaller than the HSR over the full snow cover measurement range. Because the higher frequency channels are most sensitive to snow, the baseline spectral algorithm will be most sensitive to snow cover at the higher frequency HSR and spatial errors will be negligible provided that the lower frequency HSR is not significantly greater than the HCS. We therefore chose to provide the snow cover at 20 km HCS with the assumption that spatial errors at this cell size are small compared to other error terms. At center of scan—where the sensor sampling interval is largest and footprint matching performance is worst—composite footprint spatial resolutions range from about 14x20 km at 89 GHz to 22x18 km at 18 GHz with at least 64% of the footprint weight falling in the 20x20 km cell (compared to 69% when the footprint HSR matches the cell exactly).

5.2.3. Snow Depth Ranges and Vertical Coverage Performance

The threshold requirement is for snow cover for snow of any thickness. Measurement uncertainty estimates below are based on comparisons of SSM/I-retrieval snow cover to truth from visible imagery (described in section 5.3). Since visible imagery provides snow cover without regard to snow depth, our measurement uncertainty estimates include snow cover of any snow thickness.

5.2.4. Measurement Uncertainty Performance

The following table summarizes snow cover measurement uncertainty estimates stratified by snow cover percentage. The table's measurement uncertainty values are derived from SSM/I test results using the measurement budget assumptions described in section 5.3.

Table 5-3: Snow cover predicted measurement uncertainty by snow cover range

Measurement Uncertainty [%]	Snow Cover Range [%]						
	0	>0-20	20-40	40-60	60-80	80-<100	100
Requirement	20	20	20	20	20	20	20
CMIS total error budget estimate	7	11	20	20	20	17	4

5.2.5. Measurement Range Performance

By algorithm definition, the measurement range for snow cover is 0-100%. The performance estimates in section 5.2.3 predict that measurement performance requirements are met over the full measurement range required for the product under nominal conditions.

5.2.6. Probability of correct typing performance

To be completed (for snow classification from brightness temperatures and emissivities)

5.3. Sensitivity Studies

Table 5-4 gives the derivation of our snow cover measurement uncertainty predictions summarized above. The baseline errors are from SSM/I test results detailed in section 5.5.1 and include truth errors, atmospheric effects, algorithm errors, and errors flowing from the SSM/I 70 km resolution and interpolation of the data to a 35 km grid. The SSM/I tests fail to meet the 20% measurement uncertainty requirement in the 20-80% snow cover range. In order to meet these requirements, we assume that the following reductions in error will be realized for CMIS retrievals.

- CMIS 20 km spatial resolution: 5% error reduction (RMS). Higher spatial resolution increases the number of cells that are purely bare or snow-covered and decreases the variability across and between nearby cells.
- CMIS localized calibration points: 10-30% error reduction. Spectral calibration cells are chosen by the algorithm from cells whose neighborhood is either purely bare or matches a prescribed coverage (for example, a neighborhood where 75-99% of cells in a 3x3 cell group are typed as snow). Higher CMIS spatial resolution and sampling will improve the calibration quality by providing a sufficient number of calibration cells in a smaller region. Since the algorithm assumes that the spectra of snow and bare terrain in the retrieval cell are similar to those in the calibration cells, shorter distances between the retrieval and calibration cells will enhance the algorithm. We predict up to 30% error reduction based on the comparison of retrieval tests in flat and mountainous terrain in Table 5-9. In the test, the retrieval algorithm performed best in flat terrain where the spatial variability scale of the snowpack spectra was largest—that is, the regional calibration was more accurate at the local scale. We assume that tuning of calibration

region size and other algorithm spatial parameters will provide significant performance improvement with higher resolution CMIS data.

- CMIS geolocation error: 15% error reduction. CMIS is expected to have lower geolocation errors than SSM/I and every channel will be over-sampled in the along-scan direction. We assume modest error reductions from these improvements combined with more precise interpolation to the earth grid than was possible with the SSM/I test data.

Table 5-4: Snow cover measurement uncertainty error budget

Error category	Type	Snow Cover Range [%]						
		0	>0-20	20-40	40-60	60-80	80-<100	100
Day 35 SSM/I test results	Baseline error	6.7	11.0	26.2	29.4	38.6	17.3	4.5
CMIS 20 km spatial resolution	Reduction	0	0	5	5	5	0	0
CMIS localized calibration points	Reduction	0	0	5	15	29	0	0
CMIS geolocation error	Reduction	0	0	15	15	15	0	0
CMIS atmosphere removal	Reduction	0	0	0	0	0	0	0
CMIS total error budget estimate	Baseline less reductions	7	11	20	20	20	17	4
Requirement		20	20	20	20	20	20	20

5.4. Constraints, Limitations, and Assumptions

- Measurement performance predictions are predicated on the assumptions summarized in the error budget table above. Namely, that the performance benefits from higher CMIS spatial resolution, increased localization of calibration points, and reduced geolocation errors compared to the SSM/I tests detailed in section 5.5 will be sufficient to reduce errors for snow cover between 20 and 80% to threshold levels.

5.5. Algorithm performance tests with similar sensor data

5.5.1. SSM/I snow cover retrieval tests

The snow cover algorithm was applied to a set of ascending and descending SSM/I swaths from the F13 and F14 platforms that corresponded to 1 km snow cover truth maps acquired from the National Operational Hydrologic Remote Sensing Center (NOHRSC), NWS. Table 5-5 summarizes the SSM/I and validation data. As discussed above, these tests form the basis for our snow cover retrieval performance estimates.

Table 5-5: SSM/I snow cover test scene summary

<table>
<tr><td>Date of truth scene</td><td>1-4 Feb 1999 (day 32-35)</td><td>15-18 Feb. 1999 (day 46-49)</td></tr>
<tr><td>CONUS regions selected from truth scenes</td><td>S. Dakota (SD)
Colorado (CO)
Sierra Nevada (SN)</td><td>California-Nevada (CN)
Colorado-Utah (CU)</td></tr>
<tr><td>Source of truth scene</td><td colspan="2">NOHRSC 1km analysis from visible imagery. Possible classifications are snow, no snow, and cloud (4-day persistence)</td></tr>
<tr><td>SSM/I data format</td><td colspan="2">• Brightness temperature swath format with one half-orbit per file, ascending or descending nodes, F13 or F14 platforms
• We processed TBs to match 70 km circular 3dB footprints and gridded them with 35 km HRI (i.e., EFOVs overlap)</td></tr>
<tr><td>SSM/I swath day & local time

(Note: Some swaths only partially cover the region. See maps below.)</td><td>Day 35
SD: 0600, 0900, 1800, 2100
CO: 0600, 0900, 1800, 2100
SN: 2100
Day 34
SD: 0600, 0900, 2100
CO: 0600, 2100
SN: 2100</td><td>Day 49
CN: 0600, 0900, 1800, 2100
CU: 0600, 0900, 1800, 2100</td></tr>
</table>

Table 5-6 details the retrieval performance achieved by the baseline algorithm (brightness temperature mode) for each day of SSM/I data. Required CMIS measurement uncertainty performance is shown for reference. Overall uncertainty is better than threshold but uncertainty in bins from 20 to 100% (exclusive) is usually worse than threshold.

Table 5-6: Baseline SSM/I scene retrieval performance

Baseline Conditions		Snow Cover Range [%]							Overall
		0	>0-20	20-40	40-60	60-80	80-<100	100	
Requirement	Unc.	20	20	20	20	20	20	20	20
Day 35 scenes	Unc.	6.7	11.0	26.2	29.4	38.6	17.3	4.5	16.8
	Bias	3.0	2.2	0.8	-5.0	-15.6	-3.1	-0.4	-0.7
	N	562	322	172	114	145	332	462	2113
Day 49 scenes	Unc.	6.9	12.5	24.3	30.2	28.9	23.7	14.2	19.2
	Bias	2.6	3.7	3.6	7.3	-7.0	-8.2	-5.2	-0.2
	N	615	481	241	192	208	369	149	2255
Day 34 scenes (day 35 truth)	Unc.	4.6	10.6	20.3	22.8	39.7	27.3	6.7	17.5
	Bias	1.0	2.6	-1.8	-7.7	-18.9	-12.5	-1.4	-3.3
	N	464	251	121	88	105	246	356	1633

Figure 5-1 through Figure 5-3 compare snow cover truth with SSM/I-derived gray-scale snow cover maps (0% snow = black, 100% snow = white). There is good spatial correspondence between the truth and the retrieval maps and the retrieval spans the range of snow cover fractions. Same-region retrieval consistency is good even between retrievals made on separate days (day 34 and 35) and from nighttime and daytime swaths.

**Figure 5-1: True (day 35) and retrieved (day 35) snow cover maps.
Top to bottom: South Dakota, Colorado, Sierra Nevada**

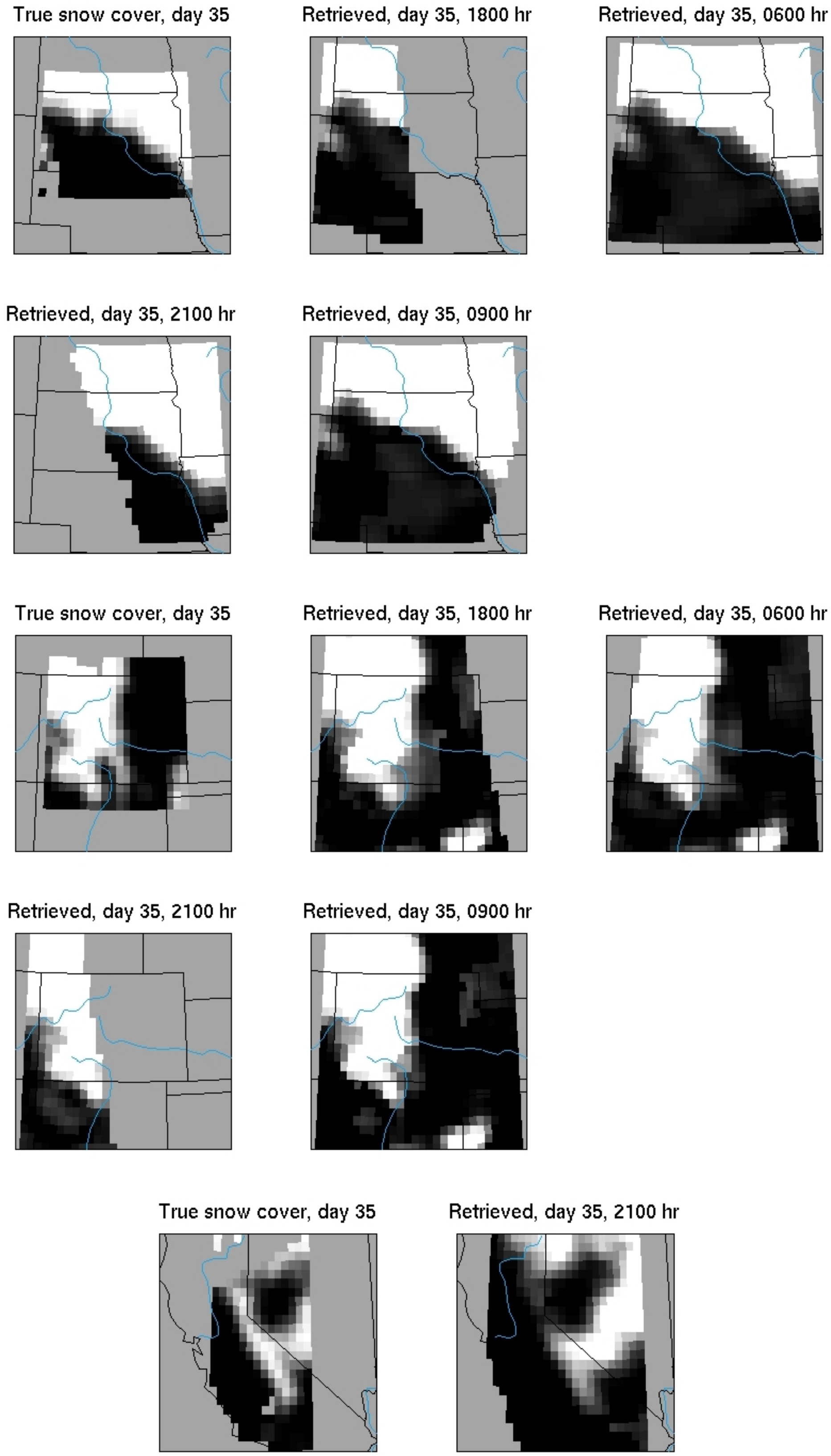


Figure 5-2: True (day 35) and retrieved (day 34) snow cover maps.
Top to bottom: South Dakota, Colorado, Sierra Nevada

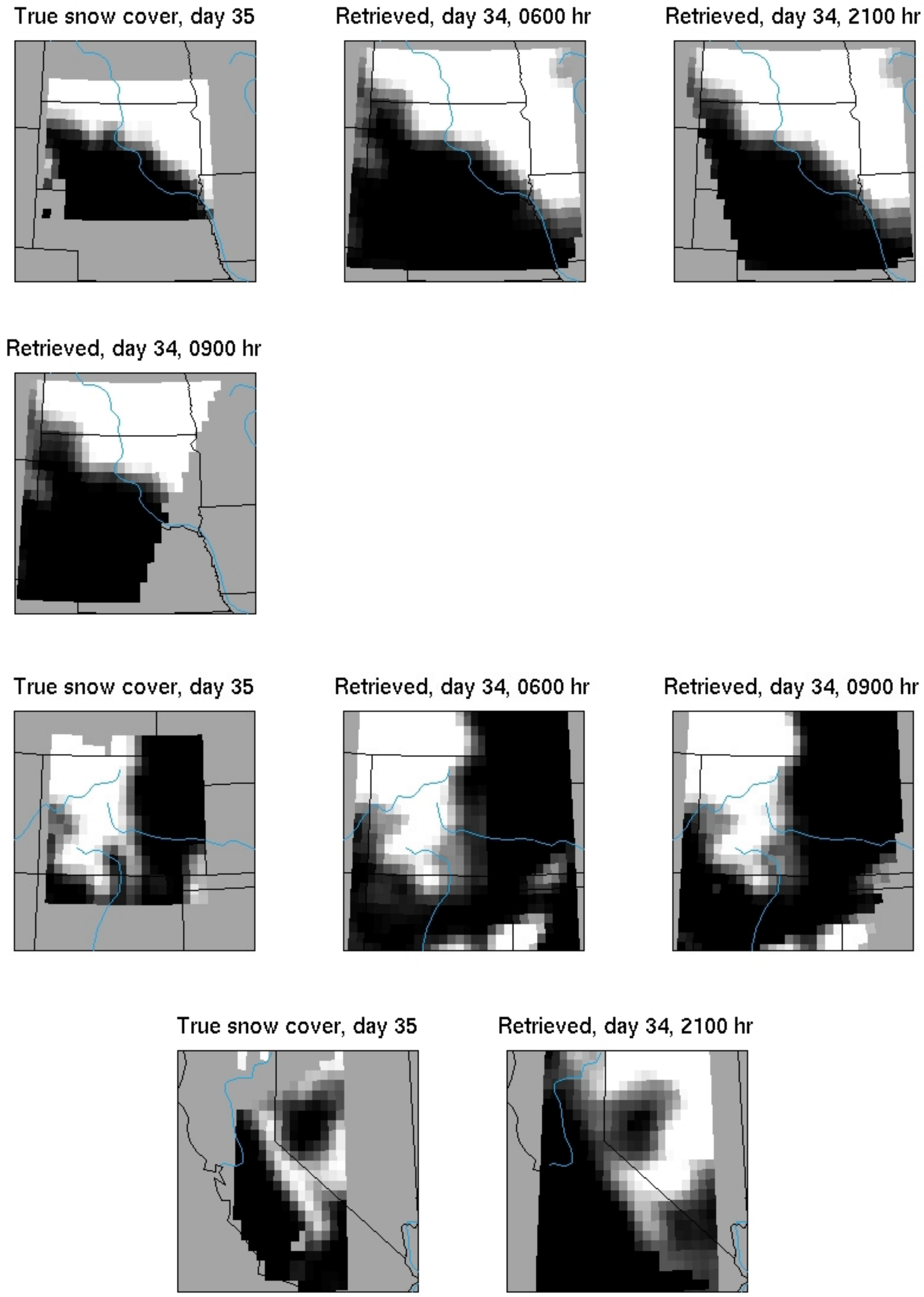
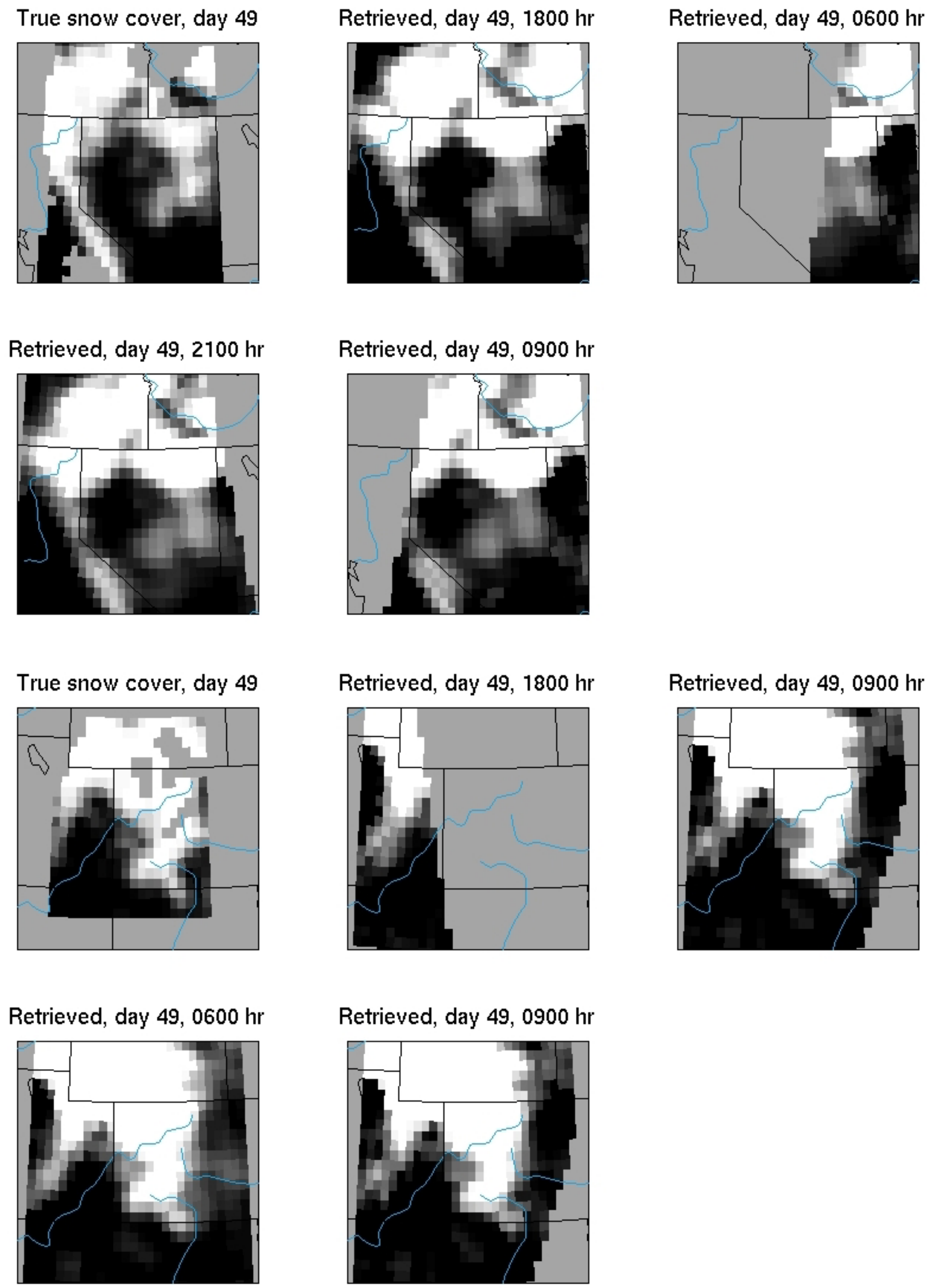


Figure 5-3: True (day 49) and retrieved (day 49) snow cover maps. Top: California-Nevada. Bottom: Colorado-Utah



5.5.2. Algorithm sensitivity studies using SSM/I dataset

The SSM/I dataset was used to test a variety of algorithm alternatives and test conditions. Table 5-7 compares the baseline spectral algorithm, which uses 22-85 GHz spectral gradients, to alternative methods using 19-85, 37-85, and 19-37 GHz gradients. There is little difference between the 22-85 algorithm and the 19-85 method. This suggests that atmospheric effects, which should differ between 19 and 22 GHz, are a relatively small component of the overall retrieval uncertainty. Also, 37-85 and 19-37 GHz alternatives give worse performance overall, indicating that channel selection should be based mostly on maximizing the spectral signature of snow and less on eliminating atmospheric effects. 166 GHz data may be able to enhance retrieval performance if it is found to have greater sensitivity to snow cover or less variability within the snow field and any additional atmospheric effects can be effectively removed by the Core Module.

Table 5-7: Day 35 SSM/I baseline performance compared to alternative spectral methods

Conditions		Snow Cover Range [%]							Overall
		0	>0-20	20-40	40-60	60-80	80-<100	100	
Requirement	Unc.	20	20	20	20	20	20	20	20
Day 35 scenes, 22-85 gradient (baseline)	Unc.	6.7	11.0	26.2	29.4	38.6	17.3	4.5	16.8
	Bias	3.0	2.2	0.8	-5.0	-15.6	-3.1	-0.4	-0.7
	N	562	322	172	114	145	332	462	2113
Day 35 scenes, 19-85 gradient	Unc.	7.4	11.5	23.9	29.3	38.8	17.4	4.2	16.9
	Bias	3.2	2.1	-0.8	-6.2	-15.6	-3.3	-0.3	-0.9
	N	542	320	171	114	145	332	462	2090
Day 35 scenes, 37-85 gradient	Unc.	9.5	12.5	26.3	34.6	14.1	29.2	9.1	21.7
	Bias	3.8	1.7	-4.2	-11.6	-23.8	-12.5	-1.4	-3.7
	N	542	320	171	114	145	332	462	2090
Day 35 scenes, 19-37 gradient	Unc.	6.5	14.5	29.7	33.9	41.0	20.2	2.1	19.1
	Bias	2.5	3.9	3.2	-5.5	-14.5	-5.1	-0.3	-0.6
	N	542	320	171	114	145	332	462	2090

Figure 5-4 illustrates the impact of wet snow. Here, the algorithm's wet snow feature is disabled and it incorrectly assigns zero snow cover to areas in North Dakota and along the North Dakota-South Dakota border, primarily at 0600 and 0900 hours. Weather station data confirms that wet snow was present at those times. Temperatures at Aberdeen in northwest South Dakota were near freezing and rising at 0600, 37º F at 0900, but had dropped to 21º F by 2100 hours with 1 inch of snow reported. Dickinson in southwest North Dakota had above freezing temperatures overnight with 34º F at 0600 dropping to 30º F at 0900 and 18º F at 2100 with 4 inches of snow. As shown in Figure 5-2, the algorithm successfully identifies these areas as snow by comparing spectral gradients (22-85 GHz) at the observation time to prior observations within a 24 hour window. (Here a *later* observation on the same day was used but the principle is the same.) Where there are large differences between the present and past gradients, a wet snow situation is assumed and the past snow cover retrieval supplants the current one. This method will detect the archetypal diurnal thaw-refreeze cycle of snow but will miss snow that remains unfrozen at observation times for more than 24 hours. Table 5-8 summarizes the retrieval errors realized for these scenes with and without wet snow detection capabilities.

Figure 5-4: True day 35 South Dakota snow cover map and day 34 snow cover map retrieved with wet snow detection disabled

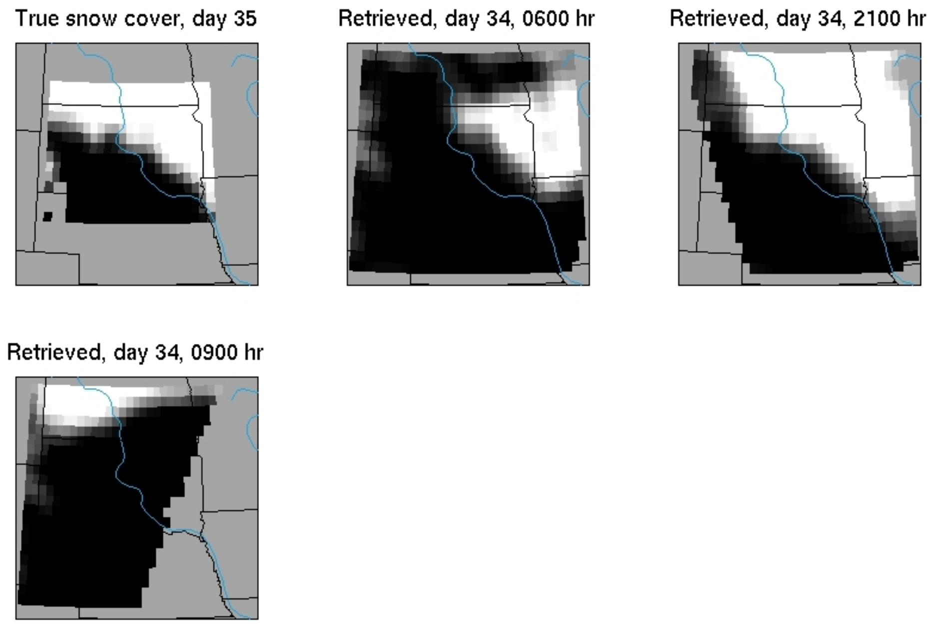


Table 5-8: Day 34 SSM/I retrieval performance with (top) and without wet snow detection capabilities

Conditions		Snow Cover Range [%]							Overall
		0	>0-20	20-40	40-60	60-80	80-<100	100	
Requirement	Unc.	20	20	20	20	20	20	20	20
Day 34 scenes (day 35 truth)	Unc.	4.6	10.6	20.3	22.8	39.7	27.3	6.7	17.5
	Bias	1.0	2.6	-1.8	-7.7	-18.9	-12.5	-1.4	-3.3
	N	464	251	121	88	105	246	356	1633
Day 34 scenes, neglecting wet snow	Unc.	4.6	10.7	21.0	30.2	44.5	47.2	53.6	34.6
	Bias	1.0	1.9	-5.3	-16.2	-26.7	-29.1	-32.0	-13.7
	N	464	251	121	88	105	246	356	1633

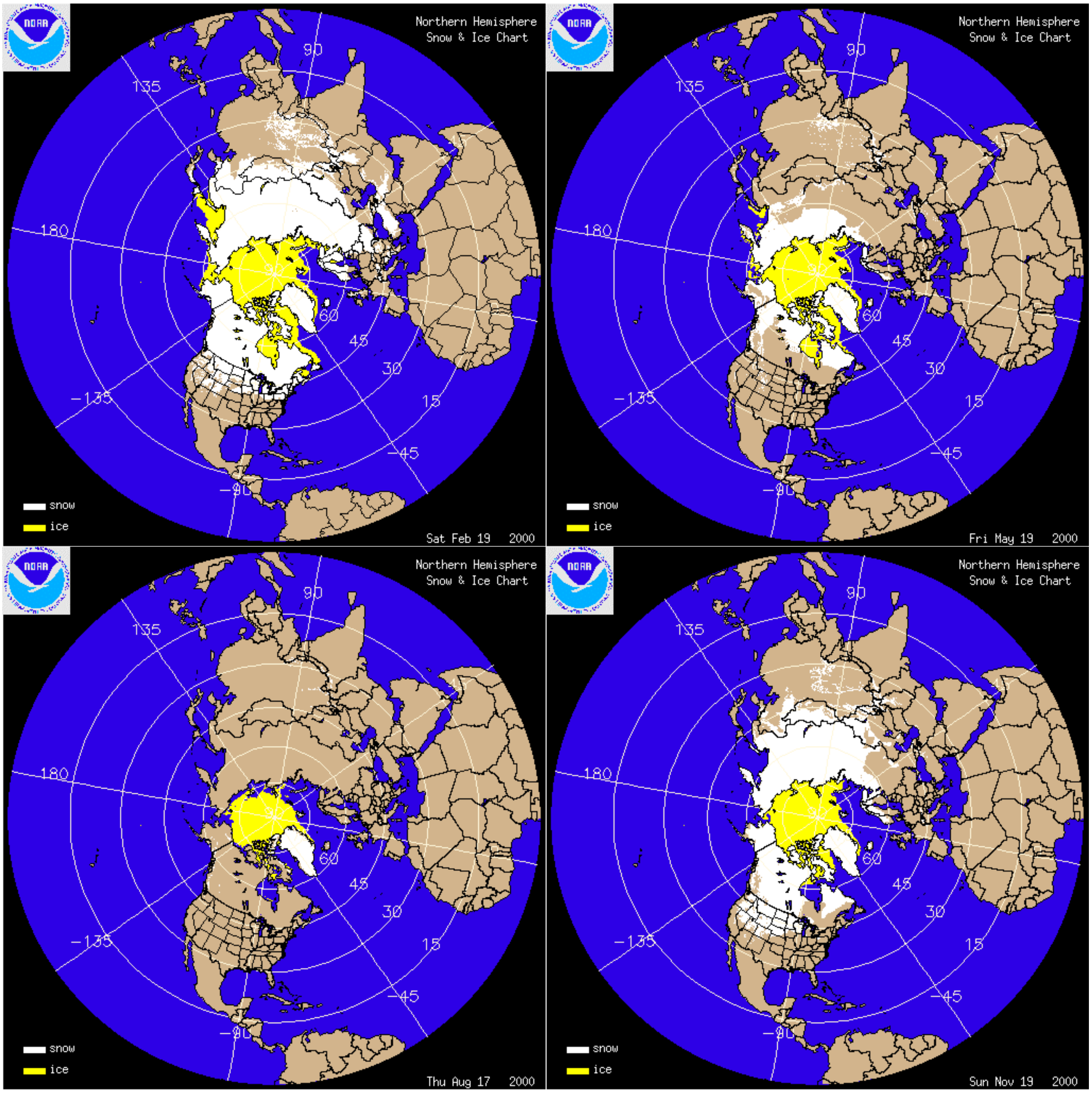
Table 5-9 breaks down day 35 baseline retrieval performance for the three test regions—South Dakota, Colorado, and Sierra Nevada. The regions represent a range of snow-line characteristics. In the South Dakota region, the snow-line separates the northern hemispheric snowpack from bare areas to the south; in the Colorado region, snow covers a broad peninsular region of high relief; and in the Sierra Nevada region, snow lies on a narrow mountain range with few cells containing 100% snow cover. The algorithm performs best in South Dakota where the spatial scales of snow cover are well-sampled by the sensor and worst in the Sierra Nevada where sub-footprint variability is greatest. The basis of the snow fraction calculation is that the spectral characteristics of cells surrounded mostly by snow-covered cells are a good approximation to the spectra of the snow-covered portions of mixed cells. The Sierra Nevada test region does not support this model with SSM/I data because there are few 100% snow cells, those that exist are far away from many of the mixed cells for which they might provide algorithm calibration points, and a cell's neighborhood is not a good model for its snow cover at any snow cover level.

Table 5-9: Day 35 SSM/I baseline retrieval performance by test region

Baseline Conditions		Snow Cover Range [%]							Overall
		0	>0-20	20-40	40-60	60-80	80-<100	100	
Requirement	Unc.	20	20	20	20	20	20	20	20
Day 35, South Dakota region	Unc.	7.8	5.2	32.5	19.2	29.1	14.0	0.0	12.2
	Bias	5.9	1.6	4.9	-3.7	-10.4	-1.9	0.0	1.4
	N	290	100	45	39	41	120	315	950
Day 35, Colorado region	Unc.	9.2	15.4	26.4	34.2	41.4	14.2	0.0	19.0
	Bias	4.4	5.8	7.7	4.0	-8.4	1.6	0.0	2.7
	N	283	172	109	67	83	185	210	1113
Day 35, Sierra Nevada region	Unc.	3.0	7.8	18.0	27.5	34.0	28.7	42.1	20.4
	Bias	0.5	-2.1	-11.4	-18.6	-17.7	-16.4	-35.5	-8.5
	N	74	72	29	25	36	37	6	279

The proportions of snow fraction retrievals that are more like the South Dakota or Sierra Nevada tests depends on the CMIS spatial resolution and sampling and global snow cover spatial characteristics. For snow cover retrievals, CMIS will have 20 km nominal spatial resolution and map sampling will be nominally 10 km. These are about three times better than the SSM/I retrievals shown above. Higher CMIS spatial sampling will allow for better localization of the algorithm calibration points and decrease the number of situations where algorithm spatial assumptions are violated. Figure 5-5 shows a sample of Northern Hemisphere snow cover maps from February, May, August, and November, 2000. The largely contiguous winter snowpacks in North America and Siberia make up the bulk of the annual snow covered area although there are many areas with discontinuous snow cover. The higher CMIS spatial resolution will help most in the discontinuous areas where the spatial scale of snow cover variations is greater than about 50 km. This criterion is easily met where snow cover variation is controlled mostly by mesoscale meteorology, not topography. Further global testing will be necessary to determine where and when topographic snow limits can also be expected to meet the 50 km threshold.

Figure 5-5: Northern Hemisphere snow cover in Feb., May, August, and Nov. 2000



Source: NOAA Satellite Services Division, http://www.ssd.noaa.gov/.

We used the SSM/I data set to examine both spatial and spectral alternatives to the baseline snow cover algorithm. Snow cover fraction is easily retrieved by spatial analysis if horizontal spatial resolution and sampling are much finer than the cell size or if the spatial scale of snow cover is much greater than the cell size. As illustrated above, for the bulk of the annual snowpack spatial scales are significantly larger than the 20 km cell size, reaching continental scales at their upper limit. In the SSM/I test scenes, conditions are more stressing because many cells have partial snow cover and topography increases the spatial complexity. Table 5-10 gives performance results for the baseline (spectral) algorithm and three spatial alternatives using the day 35 SSM/I test scenes. Each spatial algorithm is based on snow detection imagery where each cell is assigned a value of 1 or 0 if snow is or is not detected using the decision tree in Figure 3-1. As noted in Table 5-5, the SSM/I data are averaged as necessary to match a footprint with 70 km diameter at the 3dB level and are sampled at 35 km intervals. (See *ATBD for Common EDR Processing Tasks*, AER, 2000, for more details on footprint matching.)

The first spatial algorithm uses the detection value (0 or 1) as the snow cover fraction. Overall performance is poor and cells with true snow cover between 20 and 80% have the worst retrieval uncertainty. Near-zero overall bias suggests that cells are correctly typed (snow or bare) on average: 16% of all-snow cells are typed as bare, 5% of all-bare cells are typed as snow, and mixed cells are more often typed as snow than bare.

The other spatial algorithms calculate snow cover fraction as the average of the detected value (0 or 1) in the specified cell neighborhood—that is, 3x3, 5x5, or 7x7 cell groups where the retrieval cell is the one at the center of the group. The bin totals *N* for each algorithm differ because of the spatial limits of the SSM/I swaths (e.g., Figure 5-1). The tests show that a spatial algorithm is good at correctly identifying all-snow cells but at the expense of over-estimating snow fraction when the cells are mixed. The 3x3 algorithm has low overall errors but is the worst of the three in the 20-80% snow cover range. The baseline snow cover algorithm uses cells with 3x3 snow cover equal to 0 as spectral calibration points for bare ground. Positive 3x3 snow cover bias suggests that cells identified as snow-free are likely to be correctly typed. In addition, the baseline algorithm uses cells with 5x5 snow cover in the 70-<100% range to provide spectral calibration points. The low bias of the 5x5 algorithm in the 60-100% range also confirms that, on average, the 5x5 snow fraction calculated for these cells is correct. Consequently, although the spatial algorithms provide poor overall retrieval performance, they are useful for accurately providing spectral calibration data matched to specific snow cover amounts.

Table 5-10: Day 35 SSM/I baseline retrieval performance compared to spatial sampling alternatives

Conditions		Snow Cover Range [%]							Overall
		0	>0-20	20-40	40-60	60-80	80-<100	100	
Requirement	Unc.	20	20	20	20	20	20	20	20
Day 35 scenes (baseline)	Unc.	6.7	11.0	26.2	29.4	38.6	17.3	4.5	16.8
	Bias	3.0	2.2	0.8	-5.0	-15.6	-3.1	-0.4	-0.7
	N	562	322	172	114	145	332	462	2113
Day 35 scenes, snow cover from [0 1] detection	Unc.	22.7	38.0	56.9	51.0	46.6	40.8	40.4	39.0
	Bias	5.2	11.3	30.0	18.6	-1.4	-12.4	-16.3	-0.2
	N	601	298	162	117	151	393	552	2278
Day 35 scenes, snow cover from 3x3 cells	Unc.	23.9	40.3	50.2	40.5	38.0	14.9	0.0	28.7
	Bias	9.7	25.3	34.7	23.2	4.0	2.7	0.0	11.1
	N	490	290	159	112	142	328	439	1963
Day 35 scenes, snow cover from 5x5 cells	Unc.	25.2	43.7	45.7	35.4	33.6	14.7	1.0	28.6
	Bias	13.8	31.6	33.8	19.9	0.0	-1.6	-0.2	12.2
	N	498	303	158	110	133	317	414	1936
Day 35 scenes, snow cover from 7x7 cells	Unc.	30.1	45.9	42.6	33.1	31.0	16.1	3.0	29.9
	Bias	20.0	35.5	32.2	18.1	-3.9	-6.1	-1.0	13.1
	N	468	298	152	102	126	302	389	1840

One further test of spatial algorithms was performed using data to simulate CMIS spatial sampling. We resampled the 1 km NOHRSC truth scenes for day 49 to produce snow fraction in 12.5, 25, and 50 km cells. We also resampled it at 17 km HSR to simulate the CMIS 37 GHz footprints with 12.5 km sampling and applied the following rule: Where the 17 km snow fraction is greater than 0.1 detect snow, otherwise detect bare. No additional retrieval errors were simulated. The 3x3 snow cover fraction f_3 was calculated as described above and the retrieved snow cover fraction was calculated as:

$$\text{If snow is detected in cell } C = 0.2 + 0.8 f_3 \text{ else } C = 0.4 f_3 \tag{7}$$

Finally, algorithm bias was removed by retrieval bin in order to simulated an ideally well-tuned algorithm.

Table 5-11 gives simulated spatial retrieval results for three truth cell sizes. Although overall errors are better than threshold, both 12.5 and 25 km cells have some bins with worse than threshold performance. Performance improves slightly for 50 km cells, which is closest to matching the spatial extent of a 3x3 group of 17 km cells with 12.5 km spacing. These results suggest that to retrieve snow cover to better that 20% uncertainty with CMIS sampling requires a horizontal cell size of at least about 50 km even when other retrieval errors are minimized.

Table 5-11: Simulated snow cover retrieval performance from spatial analysis (algorithm alternative)

Sim. Sampling Conditions		Snow Cover Range [%]							Overall
		0	>0-20	20-40	40-60	60-80	80-<100	100	
Requirement	Unc.	20	20	20	20	20	20	20	20
Day 49 scenes, 17 km HSR, 12.5 km HCS	Unc.	4.0	33.0	35.0	29.6	19.8	15.9	12.9	17.1
	Bias	0.9	22.5	25.2	16.0	3.0	-9.4	-11.1	-1.2
	N	5901	1203	649	585	665	1464	4787	15254
Day 49 scenes, 17 km HSR, 25 km HCS	Unc.	0.9	15.5	23.9	26.4	19.6	10.4	10.5	12.9
	Bias	0.2	8.2	14.5	15.4	6.8	-6.0	-10.2	-0.9
	N	4742	1695	912	843	931	2164	2364	14551
Day 49 scenes, 17 km HSR, 50 km HCS	Unc.	0.1	9.7	20.8	25.0	18.7	8.0	10.2	12.8
	Bias	0.0	0.9	7.0	14.3	11.5	-4.5	-10.1	0.1
	N	2336	2232	1148	1088	1245	2790	1585	13324

6. Algorithm Calibration and Validation Requirements

6.1. Pre-launch

To be completed.

6.2. Post-launch

To be completed.

6.3. Special considerations for Cal/Val

To be completed.

6.3.1. Measurement hardware

To be completed.

6.3.2. Field measurements or sensors

To be completed.

6.3.3. Sources of truth data

To be completed.

7. Practical Considerations

7.1. Numerical Computation Considerations

To be completed.

7.2. Programming/Procedure Considerations

To be completed.

7.3. Computer hardware or software requirements

To be completed.

7.4. Quality Control and Diagnostics

To be completed.

7.5. Exception and Error Handling

To be completed.

7.6. Special database considerations

To be completed.

7.7. Special operator training requirements

To be completed.

7.8. Archival requirements

To be completed.

8. Glossary of Acronyms

AMSR	Advanced Microwave Scanning Radiometer
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High Resolution Radiometer
BT	Brightness Temperature [K]
CMIS	Conical Microwave Imaging Sounder
DEM	Digital Elevation Model
DMSP	Defense Meteorological Satellite Program
EDR	Environmental Data Record
EIA	Earth Incidence Angle
ESMR	Nimbus-7 Electrically Scanning Microwave Radiometer
FOV	Field Of View
IFOV	Instantaneous Field Of View
LST	Land Surface Temperature [K]
NPOESS	National Polar-orbiting Operational Environmental satellite System
RFI	Radio-Frequency Interference
RMS	Root Mean Square
RMSE	Root Mean Square Error
SDR	Sensor Data Record
SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager Sounder
TB	Brightness Temperature
TMI	TRMM Microwave Imager
TOA	Top-of-Atmosphere (i.e., measured by sensor)

TRMM	Tropical Rainfall Measuring Mission
USGS	United States Geological Survey
VIIRS	Visible/Infrared Imager/Radiometer Suite
VIRS	Visible and Infrared Radiometer System (on TRMM)
VST	Vegetation/Surface Type
VWC	Vegetation Water Content [kg/m2]

9. References

9.1. Technical Literature

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